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Relationships between potassium fertilization, removal with harvest, and soil-test potassium in corn-soybean rotations

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Relationships between potassium fertilization, removal with harvest, and soil-test potassium in corn-soybean rotations

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CHAPTER 1. GENERAL INTRODUCTION

Introduction

Potassium (K) has an important role in agriculture; it is one of the primary macronutrients used by plants. It is important for many functions such as enzyme activation, stomata activity, transport of sugars, and many others. It is present in the soil in water-soluble, exchangeable, non-exchangeable, and mineral forms. The first three forms are in continuously dynamic transformations. Redistribution of K among these three forms occurs as K is absorbed by plants and also when K is added to soil as fertilizer, manure, or crop residues. Soil tests methods that are used to estimate crop-available K estimate mainly the exchangeable K fraction.

Plant roots absorb K^+ from the soil solution that reaches the surface of roots by mass flow and diffusion. Because K is absorbed by plants in larger amounts than any other nutrients except N, a good K management practice is needed to assure good quality products and high crop yields. Soil-testing for K and the amount of K removed with harvest are used to determine K fertilization needs for crops in Iowa and most states of the U.S.A. In order to maintain desirable soil-test K (STK) levels, K removal by crops and long-term STK trends need to be taken into account.

The two major crops in Iowa and the Corn Belt are corn and soybean. Research conducted in Iowa from the 1960s to the late 1980s demonstrated the value and importance of using soil testing to monitor available K for crops and decide K fertilization practices for corn and soybean production. Research has resulted, for example, on STK interpretations and fertilizer recommendations. But with improvements in corn hybrids and soybean varieties over the past decades, grain yields have increased significantly and management practices also have changed. There is particular interest on K management for no-till management. No-till management is an important practice for soil conservation and it is an environmental friendly tillage system. Benefits of no-till (in the long-term) include reduced soil erosion, increased organic C, water infiltration, soil biological activity, reduced evaporation, and labor requirements. One of the effects of that can occur in soil managed with no-tillage and broadcast fertilization is stratification of nutrients. Potassium stratification could decrease nutrient availability for crops when the topsoil is too dry for optimal root function but water is available in deeper layers. Placing K deeper in the soil profile in fields managed with no-till could decrease the likelihood of insufficient K for crops. There has been extensive research comparing this method with the broadcast method in Iowa, and results showed that the small yield responses to banding would seldom offset increased application costs.

Several long-term studies conducted in Iowa since the 1970s have provided useful information about long-term relationships between yield and STK for corn and soybean. Long-term experiments are useful to study these relationships and better understand underlying processes. However, these studies have not used no-till management and have not evaluated K concentrations in harvested grain or K removal with harvest. Therefore, the objective of this research was to study impacts of long-term K fertilization for corn-soybean rotations managed with no-tillage and broadcast fertilization on grain yield, grain K concentration, K removal with harvest, and STK.

Thesis organization

This thesis is organized in one paper to be submitted for publication in the Agronomy Journal. The title of the paper is Relationships between Potassium Fertilization, Removal with Harvest, and Concentrations in Soil-test K for Long-Term Corn-Soybean Rotations. The paper includes sections for an abstract, introduction, materials and methods, results and discussion, conclusions, references, tables, and figures. The paper is headed by a general introduction and followed by a general conclusion section.

CHAPTER 2. LONG-TERM RELATIONSHIPS BETWEEN POTASSIUM FERTILIZATION, REMOVAL WITH CROP HARVEST, AND SOIL-TEST POTASSIUM

A paper to be submitted to Agronomy Journal by

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Abstract

Better information is needed about soil-test K (STK) and the amount of K removed with harvest because these are used to determine K fertilization rates. That is why relationships of K fertilization, grain yield, grain K concentration (GKC), K removal, and STK were studied in five Iowa sites from 1994 to 2009 for corn (*Zea mays L.)* - soybean (*Glycine max L.*) rotations managed with no-tillage. The soils were the Mahaska, Webster, Galva, Kenyon, and Marshall series (Arquertic Argiudoll, Typic Endoaquoll, and Typic Hapludolls, respectively). Treatments were a control receiving no K (K0), and broadcast K rates (KCl fertilizer) of 33 (K1) and 66 (K2) kg K ha^{-1}. Soil-test K was measured each year in two depths of soil (0 – 7.5 and 7.5 – 15 cm) by sampling all K0 plots and the K2 plots before the corn year. After the end of the last year, soil samples also were collected from depths of 0-5, 5-10, 10-15, and 15-30 cm. Yield responses to K were frequent and large only at three sites that initially or in non-fertilized plots of most years STK (0-15 cm) tested < 170 mg K kg^{-1}. Potassium fertilization effects on to GKC were observed in several years since the middle of the study for both crops, but increases were small and sometimes decreased GKC mainly in corn. Mean GKC was 16.3 and 3.2 g K kg^{-1} for corn and soybean, respectively.

The GKC was not correlated with grain yield, but K removal with crop harvest was linearly correlated with yield. Responses of K removal tended to follow the frequencies and magnitudes of yield responses. Trends over time of K removal and soil-test K were well correlated over the long term, but not from year to year. There was large stratification in fertilized plots at all sites, but the stratification increased over the 16 years of the study only at one site where the K2 rate increased STK significantly over time. The results indicated that good yield estimates are more important than GKC to estimate grain K removal across fields and years, and also that there is good correlation between K removal and soil-test K only over the long-term.

Abbreviations: CEC, cation exchange capacity; GKC, grain K concentration; NERF, north research farm; NIRF, northern research farm; NWRF, northwest research farm; SERF, southeast research farm; SWRF, southwest research farm; RCBD, randomized completely block design; SI, stratification index; STK, soil-test K.

Introduction

Potassium (K) is one of the three primary macronutrients used by plants. It is important for many functions such as enzyme activation, stomata activity, transport of sugars, and many others. Plants need K in large quantities for good quality products and high yields. Soil-testing for K and the amount of K removed with harvest are used to determine K fertilization needs for crops in Iowa and most states of the U.S.A. In order to maintain a desirable STK, K removal by crops and long-term STK trends need to be taken into account.

Corn and soybean (the two major crops in Iowa and the Corn Belt) producers need to have a good K management program to assure high yields, good grain quality, and sustained economic benefits.

Research conducted in Iowa from the 1960s to the late 1980s demonstrated the value and importance of using soil testing to monitor available K for crops and decide K fertilization practices for corn and soybean production (Mallarino et al., 1991a; Mallarino et al. 1991b). This early research was conducted using a soil-test method based on K extraction from field-moist samples used only in Iowa, which in 1991 was discontinued. Numerous studies have been conducted since the middle 1990s with the ammonium-acetate and Mehlich-3 extractants based on dried soil samples (Warncke and Brown, 1998), which are methods currently used in Iowa and most states of the U.S.A (Bordoli and Mallarino, 1998; Borges and Mallarino 2000, 2001, 2003; Mallarino et al., 2004). These studies showed that corn and soybean have a high to moderate probability of response to K fertilization when STK measured with these two tests is lower than 171 mg K kg^{-1} (15-cm sampling depth). However, work in Minnesota showed that yield responses on a Webster soil testing 150 mg K kg^{-1} occurred in only 3 of 12 site-years (Randall et al., 1997). Research in Indiana showed that corn and soybean responded to direct K fertilization when levels were less than 100 mg K kg-1 (Vyn and Janovicek, 2001; Yin and Vyn, 2002).

Inappropriate use of fertilizers and manure has resulted in water quality impairment in many regions of the U.S.A. Many farmers are taking advantage of the economic and environmental benefits of no-till practices, and its adoption has increased significantly in the last decade. A study by the USDA using data from 2000 through 2007 showed that the increase of the NT areas for four major crops (including corn and soybean) has been roughly 1.5 percent per year (Horowitz, 2010). No-till management is an important practice for soil conservation and it is an environmental friendly tillage system. Benefits of no-till (in the long-term) include reduced soil erosion, increased organic C, water infiltration, and soil biological activity; and reduced evaporation and labor requirements (Dick et al.,1989; Wagger and Cassel, 1993; Cassady and Massey, 2000; Lal et al., 2003; Souza Andrade et al., 2003).

Many studies have shown that stratification of P and K usually occur in soils managed with no-tillage and broadcast fertilization (Shear and Moschler, 1969; Griffith et al., 1977; Ketchenson, 1980; Moncrief and Schulte, 1982; Timmons, 1982; Cruse et al., 1983; Rehm et al., 1995; Mackay et al., 1987; Karathanasis and Wells, 1990; Karlen et al., 1991; Vyn and Janovicek, 2001; Mallarino and Borges, 2006; Fernandez et al., 2008; Houx et al., 2010). Both nutrients can accumulate near the soil surface due to the cycling of nutrients by plant roots from deep to shallow soil depths, minimal mixing of organic matter and surface-applied fertilizers with the soil, and limited vertical mobility of P and K in the soil profile. The aforementioned studies have shown that large and consistent stratification occurs for P but that less marked and consistent stratification occurs for K. For example, five different Kentucky soils under no-till management from 6 to 16 years had three times as much STK and five times as much soluble K in the top 5-cm soil depth compared with the 5-17 cm depth (Karathanasis and Wells, 1990). However, Shear and Moschler (1969) and Hargrove et al. (1982) found no differences in STK between no-till and conventional tillage in vertical soil layers down to 20 cm. Karlen et al. (1991) sampled a northeast Iowa field that has been managed with no-tillage and broadcast fertilization for many years. They found that soil-test P was 3.8 times higher in the top 7.5-cm layer than in the 7.5-15 cm layer, but that STK was only 2.3 times higher.

Potassium stratification could decrease nutrient availability for crops when the topsoil is too dry for optimal root function but water is available in deeper layers. Placing K deeper in the soil profile in fields managed with no-till could decrease the likelihood of insufficient K for crops, mainly in these conditions. Studies have demonstrated that banding P or K fertilizers increased yield when compared with broadcast placement for no-till corn on soils testing low to medium in P and K (Eckert and Johnson, 1985; Yibirin et al., 1993). In contrast, other studies have shown that subsurface banding had no effect on yield (Lauson and Miller, 1997; Hairston et al., 1990; Eckert and Johnson, 1985) in spite of sometimes evident STK stratification after many years of no-till management. In Iowa, Bordoli and Mallarino (1998) found no yield response of no-till corn to P planter-band or deep-band placement methods in several trials. However, they reported that grain yield often (but not always) was higher when K was deep-banded compared with broadcast or plant-band methods. The corn responses to deep-band K placement tended to occur in years and sites with low rainfall in late spring and early summer and were not clearly related to soil-test K (STK) stratification. Borges and Mallarino (2000) also reported that shallow and deep band P placement methods did not influence yield of no-till soybean compared with a broadcast placement. Both band K placement methods produced slightly higher soybean yield than the broadcast placement at a few sites, but they noted that the small yield responses to banding would seldom offset increased application costs. Buah, et al. (2000) worked on five Iowa sites and concluded that broadcasting P or K for no-till soybean was as good as or better than with a planter-band placement.

Early research evaluated long-term trends of crop yield and STK in long-term studies (Peck et al., 1965; Cope, 1981; Mallarino et al. 1991a; Mallarino et al. 1991b). Little work has been conducted during the last 20 years, however, and few of the old studies measured K removal to be able to study long-term relationships between STK, grain K concentration, K removal with harvest, and rates of K fertilization for corn and soybean rotations. As crop yields have increased significantly over time, the total amount of K removed with the harvested products also has increased. Therefore, if K removal is not balanced by applying K with inorganic fertilizers or organic amendments soil K depletion will occur. Heckman et al. (2003) found in five states a positive association between nutrient grain concentration of P, K, Zn and Fe with yield. They also reported that regardless of the STK level there was a considerable variability in grain nutrient concentration. Several studies (Yin and Vyn, 2002a, 2003; Mallarino and Valadez-Ramirez, 2005) have shown that K concentration in corn and soybean grain vary significantly across years, sites, tillage systems, and other management practices, and that there is an inconsistent relationship between K fertilization or STK with grain K concentration and that yield variation has the largest impact on K removal.

Potassium cycling and transformations in soils are complex due to interactions with several factors. Relationships between yield, K removal, and STK over time may develop differently with no-till management according to differences in soils and other growing conditions. Long-term experiments are useful to study these relationships and better understand underlying processes. Therefore, the objective of this study was to study impacts of long-term K fertilization for corn-soybean rotations managed with no-tillage and broadcast fertilization on grain yield, grain K concentration, K removal with harvest, and STK.

Materials and Methods

Locations and Treatments

Grain yield data, grain samples, and soil samples for this study were collected from plots managed with no-tillage and selected K fertilizer treatments of experiments established with the primary objective of studying tillage systems and fertilization effects on corn and soybean grain yield. Five long-term experiments were established in 1994 at five Iowa State University research farms. The sites were located at the Northeast Research Farm (NERF) near Nashua, Northern Research Farm (NIRF) near Kanawha, Northwest Research Farm (NWRF) near Sutherland, Southeast Research Farm (SERF) near Crawfordsville, and the Southwest Research Farm (SERF) near Atlantic. The soils at the sites represent typical soils of major Iowa corn and soybean production areas and include Kenyon (fine-loamy, mixed, superactive, mesic, Typic Hapludoll) at NERF, Webster (fine-loamy, mixed, superactive, mesic, Typic Endoaquoll) at NIRF, Galva (fine-silty, mixed, superactive, mesic, Typic Hapludoll) at NWRF, Mahaska (fine, smectitic, mesic, Aquertic Argiudoll) at SERF, and Marshall (fine-silty, mixed, superactive, mesic Typic Hapludoll) at SWRF.

A corn-soybean rotation was established at each site by planting both crops from the middle of April to early May of each year on adjacent areas using identical experimental designs and rotating the crops every year. Therefore, both crops of the rotation were evaluated each year. The corn hybrids and planting dates used were among those recommended for each location and, therefore, differed among locations and changed over time. The no-till planters had residue managers that swept aside residue from a width of approximately 20 cm of rows spaced 76 cm. Nitrogen rates for corn were 160 to 180 kg N ha^{-1} (Iowa recommendations are 112 to 168 N ha^{-1}) applied as anhydrous ammonia at NERF and NWRF and injected urea ammonium-nitrate solution (UAN) at other locations. Phosphorus fertilizer was applied periodically to maintain soil-test P in the optimum to high soil-test interpretation classes (16 to 30 mg P kg^{-1} according to the Bray-1 test).

Four K fertilization treatments were broadcast in the fall by hand after harvest of the previous crop and before snowfall or soil freeze using commercial granulated KCl (0-0-60) fertilizer. One treatment was a control receiving no K fertilizer. Two treatments were rates of 33 and 66 kg K ha^{-1} and were applied every year to each crop. These treatments are coded K0, K1, and K2, respectively. An additional treatment was applied every two years at a rate of 132 kg K ha^{-1} (twice the annual 66-kg-rate, coded K3) to crops grown on even years. The plots widths varied from 4.5 to 7.7 m and the length varied from 16 to 18 m long across sites. All treatments were replicated three times, and were arranged in a randomized, complete block design (RCBD).

Soil and Grain Sampling and Analysis

In 1994, soil samples (2-cm diameter cores) were taken from two depths (0-7.5 and 7.5-15 cm) from each replication before treatments were applied. Soil samples were dried at 40 °C and crushed to pass a 2-mm sieve. In order to characterize the soils at each site, a composite sample was made from the samples taken from all replications and sampling depths. Table 1 shows summarized information for soil texture, organic matter, pH, and extractable K, Ca, Mg, and cation exchange capacity (CEC). Soil texture was determined by the method described by Kettler et al. (2001). Organic matter was determined using the Walkley-Black method, pH was measured in a 1:1 soil:water mixture, and extractable cations were measured with the 1 M neutral ammonium-acetate extractant using procedures recommended in the North Central Region Publication 221 (Brown, 1998). Initial crop-available soil K (STK) also was measured on soil from each sampling depth with the ammonium-acetate extractant.

Post-harvest soil samples were taken from two depths (0-7.5 cm and 7.5-15 cm) each year from all replications of selected treatments of all trials. The samples were collected from the control treatment (K0) of corn and soybean plots, from plots receiving the K2 treatment (66-kg K ha^{-1}) that had soybean residue until 1999, and since 2000 from plots receiving the K3 treatment (132 kg-K biennial rate) that had soybean residue. Each soil sample was a composite of 10-12 randomly collected cores 2-cm in diameter. A STK stratification index (SI) was calculated as the ratio of STK of the 0-7.5 cm to that of the 7.5-15 cm sample. The five STK interpretation classes used in Iowa (Sawyer et al., 2002) for soil series at NERF, NIRF, and NWRF sites are (mg K kg^{-1}) Very Low 0 to 90; Low 91 to 130;

Optimum 131 to 170; High 171 to 200; and Very High > 200. The five classes for soil series at SERF and SWRF sites (which are classified as having high K levels in the subsoil) are (mg K kg^{-1}) Very Low 0 to 70; Low 71 to 110; Optimum 111 to 150; High 151 to 180; and Very High > 180. In fall 2009, additional composite soil samples were collected from the K0 and K2 treatments only from soybean residue from depths of 0-5, 5-10, 10-15, and 15-30 cm to study the K distribution in the last year of the study, and were analyzed for STK.

Grain yield was measured for all treatments from a central area of each plot (15-m length of three or five rows) using a plot combine. Grain sub-samples were taken from the harvest area of each plot of the K0, K1, and K2 treatments (grain from the K3 treatment was not sampled) for determination of moisture and grain K concentration. Corn and soybean yields were adjusted to 155 and 130 g kg^{-1} moisture, respectively. Grain samples were dried at 65 °C in a forced-air oven, and were ground to flour particle size in a flour mill (Magic Mill III+, Division of SSI, Salt Lake City, UT). Grain samples collected from 1994 until 2003 were analyzed by digesting samples in 70% concentrated HNO_3 and 30% H_2O_2 (Huang and Schulte, 1985) and measuring K concentration by emission spectroscopy. The grain samples collected from 2004 to 2009 were digested with concentrated H_2SO_4 and 30% H_2O_2 (Digesdahl Analysis System, Hach Inc., Boulder, CO) and measuring K concentration by emission spectroscopy. Potassium removal with grain harvest was calculated from grain yield and K concentration data.

Data Presented and Statistical Analyses

Grain yield, grain K concentration, and K removal from harvest data from both crops are presented for the K0, K1, and K2 treatments, which were the only ones analyzed for grain K concentration. Long-term STK data are presented for the K0 for both crops for the entire evaluation period, for the K2 treatment and soybean residue from fall 1994 until fall 1999, and for the K3 treatment and soybean residue since fall 2000. Profile STK data from samples collected in 2009 are presented as relative values for the sampled K0 and K2 treatments. Relative values STK values were calculated as the proportion of the STK sum across the four sampling depths for each site and fertilization rate.

Statistical analyses of crop responses and changes in STK due to the K fertilizer treatments were analyzed using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC) for a RCBD assuming fixed treatment effects and random block effects. When three treatments were evaluated, treatment means were compared by orthogonal comparisons of the control versus the average of the two fertilized treatments and also of the two fertilized treatments. Linear and non-linear regression was used to describe the relationships between yield, K concentration, and K removal across sites and years, and also to describe STK trends over time.

Results and Discussion

Potassium Fertilization Effect on Grain Yield

Table 2 shows treatment effects on corn and soybean yield for all sites and years, and also STK (15-cm depth) of the non-fertilized plots. Sites NWRF and SWRF had infrequent and small crop yield responses to K application. At NWRF, K fertilizer increased yield ($P \leq 0.10$) only in three years for corn and in one year for soybean. The two fertilizer rates differed only once (for corn in 2000), when yield was higher for the low K rate than for the control or the high rate. The highest yield increases at each site were 0.3 Mg ha^{-1} for soybean and 0.4 to 1.3 Mg ha^{-1} for corn. At SWRF, K fertilization did not increase soybean yield in any year, and the high K rate decreased yield slightly in 1996. There was a corn yield increase only in three years, and the two fertilizer rates differed only once (in 2004) when the low K rate yielded more than the control and the high rate. The highest corn yield increases each year were 0.6 to 1.2 Mg ha^{-1}.

In contrast, yield increases were more frequent and larger at the other three sites. At NERF, yield responses to K fertilizer began in 1998 for soybean and were consistent from 2000 until the end of the study. In corn, the responses began in 2000 and were consistent until the end of the study. The two K fertilizer rates differed only in one year for soybean (in 2007) but in three years for corn (2000, 2001, and 2008). At NIRF there was a consistent response to K application across the majority of the years, and significant fertilization effects started in 1996 for soybean and 1997 for corn. In soybean, there were yield increases in eight years from 1996 until 2009, and differences between the two fertilized treatments occurred only in 1996 and 2001, when the highest rate produced more yield than the low rate.

In corn, there were yield increases in 10 years from 1997 until 2009, and consistent responses every year from 2003 to 2009. The two fertilizer rates differed only in 2003, when corn yield was higher for the higher K rate. At SERF, responses to K application were not seen until the middle of the experimental period (2000 for corn and 2001 for soybean), but since then responses from both crops were observed in 6 years. The two K fertilizer rates did not differ for soybean, and differed only in two years for corn (the high rate produced more yield in 2004 but less yield in 2006).

The initial STK values before any treatment application (Table 1) explained only partially the observed yield responses across the five sites. The sites that showed the most frequent and largest yield increases from K fertilization were those initially testing Low (NIRF) or in the lower to medium range of the Optimum STK interpretation classes (NERF and SERF). The STK levels of non-fertilized plots showed large temporal variation but tended to decrease at these sites, which agrees with the more frequent yield responses in recent years. In contrast, the site with Very High initial STK (SWRF), showed the expected very infrequent statistically significant yield increases. The similarly infrequent yield responses at NWRF seem puzzling at first, because initial STK was in the middle range of the Optimum class. Previous Iowa research and interpretation guidelines (Sawyer et al., 2002) indicate that the probability of corn and soybean yield responses is 80 % for Very Low, 60 % for Low, 25 % for Optimum, 5 % for High, and less than 1 % for Very High. Study of STK levels of non-fertilized plots at this site in following years (Table 2) indicates, however, that STK levels often were High or Very High and that the infrequent yield increases were in agreement with current guidelines. Therefore, perhaps the initial STK value measured on composite samples for the entire experimental area at this site probably did not represent well high STK spatial variability or (most likely) was the result of undetermined environmental effects on STK that year.

Grain Potassium Concentration

Significant effects of K fertilization ($P < 0.10$) on the grain K concentration (GKC) of corn and soybean were less frequent and consistent than for grain yield (Table 3). This result was observed even at the three sites (NIRF, NERF, and SERF) with frequent and large yield responses to K fertilization. At NERF there were no clear soybean GKC responses until 2000, and increases were observed only in five years, whereas corn GKC increases were first observed in 1995 but occurred only in six years during the entire evaluation period. Moreover, K fertilization decreased GKC of in three corn years. The two fertilized treatments differed only in one soybean year (2006) when GKC was higher for the high K rate. At NIRF, there were no soybean GKC responses until 2003, and increases were observed in four years. The two fertilized treatments differed in two years (2004 and 2009) when GKC was higher for the high K rate. No GKC increases were observed for corn and, moreover, in two years one or both K fertilizer rates decreased GKC. At SERF occurred the most frequent soybean GKC responses. The soybean GKC increases began in 1999, and were observed in seven years until 2009, but the two K rates differed only in 2009 when only the K1 rate increased GKC. Corn GKC responses were observed only in 1995, when there was an increase only for the high K.

The GKC responses were even less frequent and inconsistent at the two sites (NWRF and SWRF) with infrequent yield responses. At NWRF, K fertilization increased GKC only at two soybean years and two corn years. The two K rates differed only in the corn years, when increases were observed only from the low K rate in 2004 and the high rate in 2008. At SWRF, K fertilization affected GKC only in four years but increasing it in two and decreasing it in the other two years. In corn, fertilization affected GKC only in three years by increasing it in two years and decreasing it in one year.

Relationships between Grain Yield, Grain Potassium Concentration, and Potassium Removal with Grain Harvest

Grain K removal results for each site-year are not shown in tables nor discussed as it can be calculated from shown grain yield and GKC. Also, the responses tended to follow the frequencies and magnitudes of responses shown for yield. This result should be expected given the infrequent and inconsistent GKC responses for both crops at most sites and years. However, in Figs. 1 and 2 we show trends over time for yield, GKC, and K removal for means across the three sites with frequent and moderate to large yield responses (NERF, NIRF and SERF) and for the two sites with little or no yield response (NWRF and SWRF). An obvious result shown by both figures is the high temporal variation for all three measurements but especially for yield, even though these are means across two or three sites. This large impact of environmental conditions on yield, probably expected, can be seen more clearly in this figure than in Table 2.

Trends for means for the three yield responsive sites (Fig. 1) show an increase of the response to K application with time for yield, GKC, and K removal compared with the control (K0) treatment. There were little or no differences between treatments in the first few years, especially in yield for both crops, and the same result can also be seen for the other measurements. The K removal trends for both the absolute values and the responses to the treatments reflected mainly yield levels and yield responses. Trends for means of the two sites with infrequent yield responses obviously show little or no yield responses (Fig. 2). The yield trends for soybean show an apparent response to the low K rate (K1) mainly in the early years. This response was confirmed for some years by the statistical analysis of combined data from the two sites, but was not confirmed by the analyses by site (Table 1). This result is puzzling, and we have no reasonable explanation that would agree with STK values and expectations. The trends for GKC and K removal for soybean and trends for all three measurements for corn show no clear or frequent treatments effects.

Figure 3 shows the relationship between GKC and yield for corn and soybean across all sites, years, and treatments. There was no significant relationship between GKC and yield level for any crop. This result across sites and years is useful because GKC is used together with yield to decide maintenance K fertilization rates in Iowa and many states, and also because many producers and crop consultants believe that higher crop yield also imply higher GKC. Study of relationships for early years and recent years (not shown) did not improve the relationships. The means of GKC values in this study were 16.3 g K kg^{-1} for soybean and 3.2 g K kg^{-1} for corn. These values are lower than the average suggested in Iowa, which are 22.3 g K kg^{-1} for soybean and 4.20 g K kg^{-1} for corn (Sawyer et al., 2002). The suggested average values for Iowa were in the upper range of observed values.

Figure 4 shows a strong linear relationship between K removal and the yield level for both soybean and corn (r^2 of 0.83 and 0.68, respectively). A significant relationship should be expected because yield is used to calculate K removal together with GKC. The strength of the relationship confirms, however, the observation made before in that K removal responses tended to follow yield responses closer than GKC responses. In spite of apparently moderate to large variation in GKC across sites, years, and treatments (Table 2 and Figs. 1 and 2), the yield level and response have the most clear and consistent impact on K removed with harvest.

Figure 5 shows trends over time for the cumulative K removal with grain harvest and STK for the corn-soybean rotation at each site. For this figure we used the experimental area at each site that began with corn in 1994. Results for the experimental area that began with soybean in 1994 are not shown because the most essential results and conclusions were the same. This figure shows that the cumulative K removal across years showed the expected linear decline, with a very high r^2 of 0.99 at all sites. It can be seen that SWRF had more cumulative K removal (close 800 kg K ha^{-1}) than the other sites, which reflected high yield levels and often higher GKC than at other sites. This result is in agreement with the steepest decline of K removal on time among the sites (with a slope of -44 kg K ha^{-1}), although the cumulative removal decline at NERF had a similar steep slope. Soil-test K (15-cm depth) declined over time at all sites, which is an expected result due to K removal with harvest. The rate of decline was linear at most sites, except at NERF. The linear decreasing trends ranged from 2.5 to 3.8 mg K kg^{-1} yr^{-1}. The less steep decline was observed at NWRF and SERF, and the steepest was at SWRF, which was the site with the highest initial STK. The decreasing STK trend at NERF reached an obvious plateau during the last half of the experimental period, with a high r^2 of 0.68. Other research has shown similar plateau at very low soil-test levels (Peck et al., 1965; Cope, 1981; Mallarino et. al, 1991b).

A decline over time for both cumulative K removal and STK supports the generally accepted fact in the Midwest of the USA that the cumulative K removal with harvest is an important factor explaining the decrease of STK over time. Although the site with the highest K removal and steepest cumulative decline (SWRF) also showed the steepest STK decline, the relationship between decreases for each measurement was not exactly the same in all sites. Moreover, the relationship between the two measurements often did not hold over a period of one or two years. Study of measured soil properties (Table 1) together with K removal did not help at explaining differences in rates of STK decline across sites. Several other factors could be related to this difference, such as soil mineralogical properties and environmental factors influencing the measurement of crop-available soil K by soil testing. The lack of a good correlation between K removal and STK over a short period emphasizes that producers should not make decisions about maintenance K fertilization based on yield and STK from one year, but rather should look at previous information over a few years.

Long-Term Soil-Test Potassium Trends

Figure 6 shows STK trends over time for the two treatments sampled at each site (K0 and K2/K3 and the two soil sampling depths (0 - 7.5 and 7.5 - 15 cm). It is important to highlight the high variability across years for both treatments and both depths in most sites. This was also observed for average STK for the 15-cm layer (Table 2). Such a high temporal variability is typical for STK, and has been observed by other long-term Iowa research (Mallarino et al., 1991a and 1991b). Another clear result shown by Fig. 6 is the stratification of STK. Soil-test K of the shallowest soil depth was higher than in the deeper depth for both treatments with few exceptions. Most exceptions occurred at NWRF probably due to higher variability, because the magnitudes of differences were similar to or greater than at other sites. Stratification is known to occur with no-till, but this long-term evaluations at five experimental sites are the first documents for Iowa and neighboring states. Potassium stratification occurs with no-till and broadcast fertilization due to lack of mixing of the fertilizer with soils, recycling from deeper layers, and limited K movement through soil.

Soil-test K for non-fertilized plots tended to decreased over time, but this trend sometimes did not reach statistical significance at $P \leq 0.10$ for both sampling depths. For the non-fertilized plots, the decreasing trends were significant for both depths at most sites, which agree with trends for the 15-cm STK averages shown in Fig. 5. The only exception was for the shallowest depth at NWRF, which is probably explained by a seemingly very high outlier in 2004. The trends usually were linear with a decrease in the range of 1.1 to 6.8 mg K kg^{-1} yr^{-1}. The most gradual slope was observed at NWRF, and the steepest slope at SWRF for the shallower layer, which was the site that had the highest initial STK. The decreasing trends at NERF reached an obvious plateau during the last half of the experimental period, which also agrees with results for the 15-cm averages shown in Fig. 5.

Soil-test K for the fertilized plots showed no significant trends over time, with the only exception of the shallowest depth for NERF and NWRF. A general lack of STK increase for the fertilized plots is not surprising because the application rate of 66 kg K ha^{-1} applied annually or twice this rate applied every two years was purposely planned to maintain initial STK based on previous research results. Yield levels were the lowest at NWRF for both crops, where the increasing trend was steepest, which may explain an STK buildup due to less removal, but yields levels at NERF were among the highest among the sites. The STK buildup at the NERF site might be explained by the soil properties, because the soil had the coarsest texture of all sites and the lowest CEC together with SWRF (Table 1).

The change over time in the degree of stratification was not consistent across treatments and sites (Figs. 6 and 7). Changes in SI over time shown in Fig. 7 were significant ($P < 0.10$) only at three sites, where it increased for fertilized plots at NWRF but decreased over time for non-fertilized plots at SERF and also for both K treatments at SWRF. A lack of frequent and consistent fertilization effects on STK stratification over time is reasonable because significant increasing stratification over time should be expected when broadcast fertilization clearly increases STK, which was not the case in this study.

In order to study STK stratification better, profile soil samples were taken after the last soybean harvest of the study at 5-cm increments to a depth of 15 cm, and one final from 15-30 cm depth (Fig. 8). There was large STK stratification and differences between surface and deep soil layer were proportionally greater for the fertilized plots. For the non-fertilized plots, there was no significant K stratification at NWRF, SERF and SWRF, but there was a significant difference between STK for the shallowest 5-cm layer and layers below a 10-cm depth at NERF and NIRF. For the fertilized plots, there was a clear significant difference between STK in shallower 5-cm layer (0-5 cm) and the deeper soil layers at all sites. Also, at NERF, the deepest layer (15-30 cm) had lower STK than all the shallower layers. We cannot explain the more pronounced stratification with depth at this site because no samples deeper than 15 cm were collected in previous years.

Summary and Conclusions

A crop yield response to K fertilizer application was found for sites where initial STK was in the Low interpretation class, and also in two sites with initially Optimum STK that decreased to a Low level over time. The frequency and magnitude of the responses tended to increase over time, which is expected as STK of non-fertilized plots declines. No frequent or large yield responses were observed for two sites with STK initially in the Very High class or that varied between Optimum and Very High over time. Fertilization had a lesser effect on GKC of both crops compared with effects on yield, although increases also tended to be more frequent and larger in the recent years mainly at the three sites with the lower STK. Averages of GKC in this study were 16.3 g K kg^{-1} for soybean and 3.2 g K kg^{-1} for corn, being lower than the average values suggested in Iowa. Currently suggested average GKC for both crops were in the upper range of observed values. Potassium removal with grain harvest tended to follow trends for yield levels and for yield responses, because differences were proportionally much higher than differences in GKC. Therefore, these results suggest that good yield estimates are more important than GKC estimates to estimate grain K removal over time.

Cumulative K removal showed a strong linear regression over the years in all sites, and at the same time STK also decreased over time. An important result was that K removal and STK were very poorly correlated in the short term although relationships hold over several years. However, the relationship between the two rates of decline varied across sites and could not be fully explained on the basis of K removal and measured soil properties such as texture, extractable cations, or cation exchange capacity. These differences might be explained by other soil properties, such as mineralogy, and environmental factors influencing K recycling with crop residue and the estimate of crop-available soil K by soil testing.

There was significant stratification of STK in the top 30-cm of soil at all sites, which tended to be proportionally larger for the fertilized plots. However, there was no clear or consistent change over time in stratification across sites for non-fertilized or fertilized plots. This result was explained by fertilization rates that in general did not increase STK significantly over time. The only clear stratification increase over the 16 years of the study was observed for the one site where K fertilization significantly increased STK of the shallowest sampling depth over time.

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Table 1. Soil properties for five long-term experiments at five Iowa locations.

Soil classification			Soil properties						
Site	Series	Great group	Clay	OM †	pH	Ca	Mg	K	Class ‡
			---- g kg^{-1}----			----- mg kg^{-1} -----			
NERF	Kenyon	Typic Hapludoll	253	40	6.6	2872	353	140	O
NIRF	Webster	Typic Endoaquoll	319	58	6.5	4204	661	122	L
NWRF	Galva	Typic Hapludoll	375	47	6.2	3488	575	148	O
SERF	Mahaska	Arquertic Argiudoll	293	44	5.5	2408	582	131	O
SWRF	Marshall	Typic Hapludoll	291	40	6.6	2886	328	238	VH

† OM, organic matter.

‡ Class, Iowa State University soil-test K interpretation classes: L, Low; O, Optimum; VH, Very High.

Table 2. Soybean and corn grain yield as affected by the K application rate.

		Soybean				Corn			
			Treatment ‡				Treatment		
Site	Year	STK †	K0	K1	K2	STK	K0	K1	K2
		mg kg^{-1}	--------- Mg ha^{-1} -------			mg kg^{-1}	--------- Mg ha^{-1} ---------		
NERF	1994	133	4.1	3.9	3.8	148	8.5	8.5	8.5
	1995	147	2.7	2.9	2.9	141	6.8	6.6	7.0
	1996	111	4.0	4.1	4.0	115	10.2	9.7	10.1
	1997	119	4.1	4.3	4.2	129	10.0	10.1	10.6
	1998	122	3.7b	3.9ab	4.0a	114	10.1	10.2	10.2
	1999	110	3.6	3.6	3.6	112	10.4	10.9	10.8
	2000	118	3.5b	3.8a	3.8a	112	10.5b	10.8b	11.1a
	2001	108	3.0b	3.4a	3.5a	101	10.7b	10.5b	11.8a
	2002	97	2.9b	3.2a	3.4a	93	10.2b	12.1a	12.5a
	2003	86	2.2b	2.5a	2.5a	84	7.2b	8.0ab	8.6a
	2004	90	3.2b	3.5a	3.6a	100	11.3b	12.1ab	12.5a
	2005	90	4.0b	4.6a	4.6a	92	9.4b	12.0ab	12.8a
	2006	86	3.5b	3.9ab	4.0a	84	10.3b	12.5a	12.9a
	2007	113	3.4c	4.4b	4.6a	106	9.9b	11.1a	11.8a
	2008	116	3.2b	3.8a	4.1a	106	21.1b	12.2b	12.7a
	2009	89	3.3b	4.0a	4.1a	91	11.1b	13.8a	14.6a
NIRF	1994	124	2.9	3.2	3.2	121	10.2	10.3	10.2
	1995	171	3.4	3.5	3.2	194	9.4	9.6	9.5
	1996	157	2.3b	2.5b	2.8a	181	9.7	9.7	9.8
	1997	165	2.5	2.6	2.7	165	6.6b	7.5a	7.0ab
	1998	156	3.1b	3.3ab	3.4a	153	7.9	8.3	7.7
	1999	121	2.8b	3.1ab	3.3a	120	8.5b	10.3a	10.2a
	2000	142	2.4b	2.9ab	3.3a	134	6.3b	8.6a	9.2a
	2001	153	2.5c	2.8b	3.1a	155	9.7	9.3	9.5
	2002	168	2.4	2.7	2.9	178	8.4	9.1	9.1
	2003	100	2.2	2.4	2.4	112	9.9b	9.9b	10.9a
	2004	120	2.8	3.0	3.1	139	8.7b	10.9a	11.3a
	2005	126	2.5b	3.0a	3.2a	127	6.6b	9.9a	10.1a
	2006	115	3.0b	3.5a	3.6a	113	9.6b	11.8a	12.2a
	2007	155	2.1	2.8	2.8	133	6.1b	9.2a	9.5a
	2008	129	1.9b	2.6a	2.9a	140	8.5b	11.7a	12.1a
	2009	106	2.1b	2.5ab	2.6a	111	8.9b	9.5a	9.8a

† STK, initial soil-test K for the first year and thereafter for samples collected before planting each crop from the non-fertilized (K0) plots (averages for sampling depths of 0-7.5 and 7.5-15 cm).
‡ Values followed by the same letter within each row and crop indicate no treatment differences at $P \leq 0.10$.
(Table continues in the next page)

Table 2 continued.

Site	Year	Soybean STK †	Soybean Treatment ‡ K0	Soybean Treatment ‡ K1	Soybean Treatment ‡ K2	Corn STK	Corn Treatment K0	Corn Treatment K1	Corn Treatment K2
		mg kg^{-1}	--------- Mg ha^{-1} -------			mg kg^{-1}	--------- Mg ha^{-1} ---------		
NWRF	1994	154	2.8	2.9	2.8	143	10.3	9.9	9.8
	1995	232	3.0	3.0	3.0	205	6.7	7.0	7.1
	1996	187	2.0	2.0	2.1	262	7.7	7.3	7.3
	1997	228	2.7	2.6	2.6	183	7.2	7.7	7.6
	1998	223	2.9	3.0	2.9	261	8.9	9.2	8.7
	1999	219	3.3	3.3	3.1	129	9.6	9.6	9.5
	2000	173	2.5	2.5	2.5	215	7.4b	7.8a	6.8c
	2001	223	3.0	2.9	3.0	172	7.1b	8.4a	7.7ab
	2002	200	2.2	2.4	2.3	228	7.4	7.3	7.6
	2003	191	2.4	2.5	2.5	131	8.2	8.7	8.6
	2004	127	1.8	1.8	1.7	196	5.8	5.8	5.5
	2005	296	3.5b	3.8a	3.8a	226	9.2	9.3	9.3
	2006	144	3.0	3.1	3.1	232	8.9	9.0	8.4
	2007	220	4.1	4.2	4.1	163	8.6	9.0	8.8
	2008	154	3.5	3.4	3.5	193	11.1	11.3	11.3
	2009	244	3.8	4.0	3.8	181	10.5b	11.3ab	11.6a
SERF	1994	129	4.0	3.9	4.0	134	10.6	10.7	10.4
	1995	139	3.9	3.7	3.9	132	8.2	8.3	8.2
	1996	116	3.5	3.5	3.5	145	8.6	9.5	9.5
	1997	129	3.6	3.5	3.4	148	8.5	9.2	9.2
	1998	148	4.1	4.1	4.0	145	8.6	8.7	8.8
	1999	131	4.0	4.1	4.0	138	11.0	11.3	11.7
	2000	132	3.0	3.1	2.9	131	9.7b	10.1ab	10.6a
	2001	118	3.3b	3.5a	3.5ab	130	6.8	7.5	7.6
	2002	157	3.0	3.1	2.9	144	10.0	10.0	10.3
	2003	108	2.6b	3.0a	2.9a	111	10.4b	11.3a	11.4a
	2004	102	3.8	3.9	3.9	100	11.4b	11.7b	12.6a
	2005	122	3.4b	3.9a	3.8ab	120	9.2	9.2	8.7
	2006	111	3.6b	3.9a	4.0a	108	10.3c	12.0a	11.6b
	2007	125	3.6b	4.0a	3.8ab	123	9.0b	11.5a	11.3a
	2008	107	3.4b	3.9a	3.9ab	116	10.7	10.9	11.0
	2009	94	3.7	4.0	3.9	98	11.5b	12.9a	12.5ab

† STK, initial soil-test K for the first year and thereafter for samples collected before planting each crop from the non-fertilized (K0) plots (averages for sampling depths of 0-7.5 and 7.5-15 cm).

‡ Values followed by the same letter within each row and crop indicate no treatment differences at $P \leq 0.10$.

(Table continues in the next page)

Table 2 continued.

		Soybean				Corn			
			Treatment ‡				Treatment		
Site	Year	STK †	K0	K1	K2	STK	K0	K1	K2
		mg kg^{-1}	--------- Mg ha^{-1} -------			mg kg^{-1}	--------- Mg ha^{-1} ---------		
SWRF	1994	261	4.4	4.3	4.1	215	10.3	10.1	10.1
	1995	198	3.7	3.6	3.6	236	9.1	9.7	9.8
	1996	198	3.5a	3.6a	3.4b	219	9.9	9.6	10.1
	1997	156	3.8	4.0	3.9	216	10.3	10.3	10.7
	1998	215	3.4	3.5	3.5	231	10.3	11.3	10.4
	1999	232	4.2	4.2	4.2	216	7.9	7.9	8.4
	2000	185	3.4	3.3	3.2	224	9.1b	9.9a	9.5ab
	2001	198	3.5	3.5	3.3	301	11.3	11.3	11.5
	2002	205	2.0	2.2	2.3	250	8.2	7.2	6.9
	2003	167	2.0	2.0	2.0	183	8.4	7.9	8.0
	2004	186	4.3	4.2	4.2	152	13.7b	14.3a	13.8b
	2005	179	4.0	4.0	4.1	204	11.8	12.9	12.1
	2006	192	4.4	4.4	4.2	159	12.4	12.9	13.0
	2007	181	3.6	3.8	3.8	204	12.1	12.0	12.0
	2008	173	3.7	3.6	3.8	179	13.6	13.4	13.4
	2009	153	5.1	4.9	4.9	146	13.5b	14.7a	15.0a

† STK, initial soil-test K for the first year and thereafter for samples collected before planting each crop from the non-fertilized (K0) plots (averages for sampling depths of 0-7.5 and 7.5-15 cm).

‡ Values followed by the same letter within each row and crop indicate no treatment differences at $P \leq 0.10$.

Table 3. Soybean and corn grain K concentration as affected by K application rate. †

		Soybean			Corn		
		K0	K1	K2	K0	K1	K2
Site	Year	Grain concentration			Grain concentration		
		------------ g kg^{-1} ------------			------------ g kg^{-1} ------------		
NERF	1994	13.9	13.8	14.6	3.1a	3.0b	3.0ab
	1995	16.9	16.3	15.1	3.2b	3.3ab	3.4a
	1996	15.1	15.1	15.7	2.9	3.1	2.8
	1997	16.3	16.0	16.3	3.1	3.2	3.3
	1998	17.3	18.7	18.4	3.8	3.8	3.6
	1999	16.6	17.0	16.7	3.5b	3.8a	3.8a
	2000	17.2b	18.7a	18.7a	3.4	3.8	3.7
	2001	15.3	15.8	16.1	3.8a	3.3b	3.4b
	2002	17.5	17.6	17.8	3.3b	4.1a	4.0a
	2003	16.6b	18.5a	18.8a	5.1a	4.7b	4.6b
	2004	16.3	18.7	23.3	3.8	3.7	4.0
	2005	14.7b	16.1a	16.5a	3.8b	3.9ab	4.0a
	2006	14.6c	16.0b	17.1a	3.5	3.2	3.3
	2007	15.3	15.8	16.3	3.3	3.1	3.4
	2008	14.1b	16.0a	16.3a	2.9b	3.1a	3.1ab
	2009	14.5	15.1	15.4	3.0b	3.1ab	3.2a
NIRF	1994	13.9	14.6	15.3	2.8	2.7	2.7
	1995	14.9	15.8	15.0	2.9	3.0	2.9
	1996	14.2	13.5	14.4	2.8	2.7	2.6
	1997	14.2	14.9	15.4	2.7	2.7	2.9
	1998	15.5	16.4	16.7	3.2	3.2	3.1
	1999	15.7	15.7	16.4	3.7ab	3.9a	3.4b
	2000	15.4	15.1	17.2	3.9	3.6	3.8
	2001	16.1	16.4	15.8	3.3	3.3	3.4
	2002	18.1	18.0	18.8	3.7	4.1	3.6
	2003	16.2b	18.0a	17.9a	3.7	3.8	3.6
	2004	13.9c	15.0b	15.9a	3.5	3.6	3.4
	2005	16.3	16.7	17.7	3.4	3.6	3.5
	2006	14.0b	14.9ab	16.0a	.	3.4	3.4
	2007	13.8	14.6	14.7	3.5	3.6	3.5
	2008	12.7	14.2	13.1	3.5a	3.1b	3.1b
	2009	12.9b	13.2b	14.3a	2.5	2.8	2.6

† Values followed by the same letter within each row and crop indicate no treatment differences at $P \leq 0.10$. Corn grain samples for the control were lost in 2006.
(Table continues in the next page)

Table 3 continued

Site	Year	Soybean K0	Soybean K1	Soybean K2	Corn K0	Corn K1	Corn K2
		Grain concentration			Grain concentration		
		------------ g kg^{-1} ------------			------------ g kg^{-1} ------------		
NWRF	1994	16.7	16.5	16.0	2.6	2.4	2.3
	1995	14.7	15.3	15.0	3.0	3.1	3.0
	1996	15.7	16.1	16.1	2.8	2.8	2.8
	1997	15.5	15.9	16.2	2.3	2.5	2.4
	1998	17.6b	18.2a	18.5a	3.2	3.3	3.2
	1999	16.9	17.2	16.3	3.7	3.4	3.3
	2000	17.8	17.7	18.3	3.4	3.4	3.5
	2001	15.4	15.5	16.9	3.4	3.5	3.5
	2002	16.0	16.7	16.3	3.0	2.6	2.4
	2003	17.7	18.4	18.8	3.4	3.5	3.6
	2004	15.9b	16.4a	16.6a	3.1b	3.3a	3.2b
	2005	15.3	15.5	15.3	2.4	1.6	2.5
	2006	14.3	14.4	14.7	.	2.7	2.8
	2007	14.5	14.8	15.4	2.7	2.7	2.8
	2008	13.7	14.4	14.2	2.7ab	2.5b	2.8a
	2009	16.2	16.5	17.0	3.0	3.0	3.0
SERF	1994	15.1	15.3	15.4	2.8	2.8	2.8
	1995	16.5	16.8	16.5	2.9b	2.8b	3.1a
	1996	15.5	15.7	15.5	2.8	2.9	2.8
	1997	15.2	15.3	15.1	2.7	2.6	2.7
	1998	17.3	17.3	17.8	3.3	3.3	3.4
	1999	16.7b	18.3a	17.8a	3.5	3.6	3.8
	2000	18.4b	19.4ab	19.7a	3.6	3.1	3.1
	2001	16.1	16.8	17.4	3.3	3.4	3.3
	2002	17.1b	18ab	18.2a	2.9	2.9	3.0
	2003	16.8	17.2	18.8	2.9	2.9	3.1
	2004	14.8b	15.5a	15.8a	2.9	2.7	2.9
	2005	14.3b	15.4a	15.9a	3.1	3.1	3.2
	2006	15.4	16.5	16.2	.	2.5	2.6
	2007	15.2b	16.4ab	16.9a	3.5	3.7	3.7
	2008	13.8	13.6	14.3	2.6	2.7	3.2
	2009	16.9ab	17.4a	16.3b	3.2	3.3	3.3

† Values followed by the same letter within each row and crop indicate no treatment differences at $P \leq 0.10$. Corn grain samples for the control were lost in 2006.

(Table continues in the next page)

Table 3 continued

Site	Year	Soybean K0	Soybean K1	Soybean K2	Corn K0	Corn K1	Corn K2
		Grain concentration			Grain concentration		
		------------ g kg^{-1} ------------			------------ g kg^{-1} ------------		
SWRF	1994	14.7	15.4	14.4	3.0	3.0	3.0
	1995	15.8	15.1	15.7	2.5	2.6	2.6
	1996	17.8	18.5	18.6	2.7	2.7	2.8
	1997	17.6	17.7	17.3	3.0	2.7	3.0
	1998	17.3	16.8	17.3	3.0	2.9	2.9
	1999	18.5	18.7	18.3	3.6	3.9	3.8
	2000	19.7b	19.5b	21.4a	3.6	4.0	3.7
	2001	15.4	15.2	15.7	3.3a	3.5a	3.1b
	2002	19.8	21.0	19.3	2.8	3.5	2.9
	2003	19.7	20.3	21.9	3.8	3.9	3.6
	2004	16.1	16.9	15.8	3.2	3.2	3.3
	2005	16.0	16.0	16.4	3.1b	3.4a	3.1b
	2006	16.7a	16.5b	16.4b	.	3.0	3.2
	2007	16.4	16.3	16.8	3.2	3.4	3.3
	2008	15.1b	15.4ab	15.5a	3.0	2.9	3.1
	2009	16.8a	16.4ab	16.3b	2.8b	3.1a	3.3a

† Values followed by the same letter within each row and crop indicate no treatment differences at $P \leq 0.10$. Corn grain samples for the control were lost in 2006.

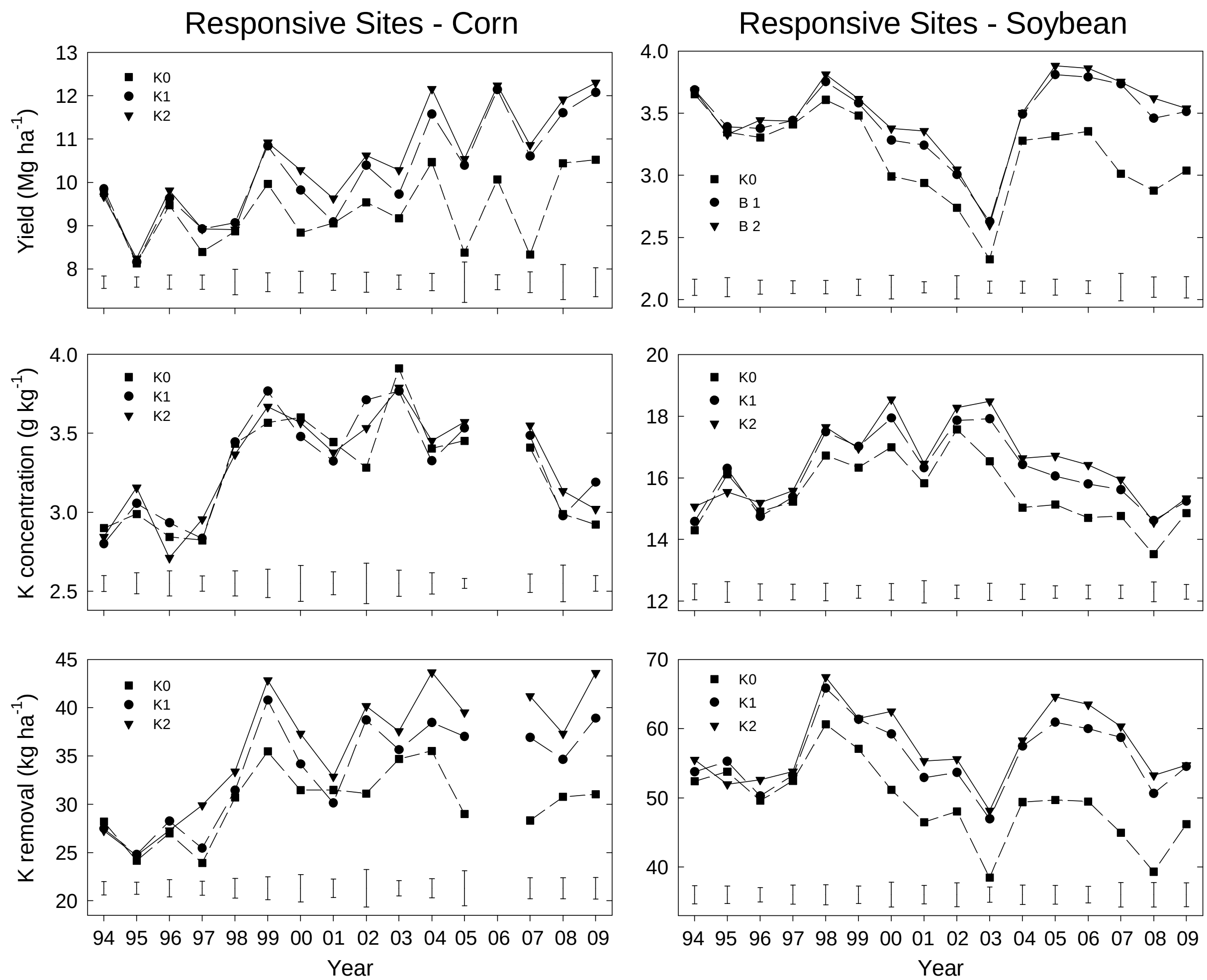

Figure 1. Mean trends over time for yield, grain K concentration, and K removal across the three yield responsive sites (NERF, NIRF, and SERF). K0 refers to the control (0 kg K ha^{-1}) treatment and K1 and K2 refers to 33 and 66 kg K ha^{-1} respectively. Corn grain samples were lost in 2006, so no data was included for any treatment. Vertical lines at the bottom of each graph indicate standard errors of a treatment mean for each year.

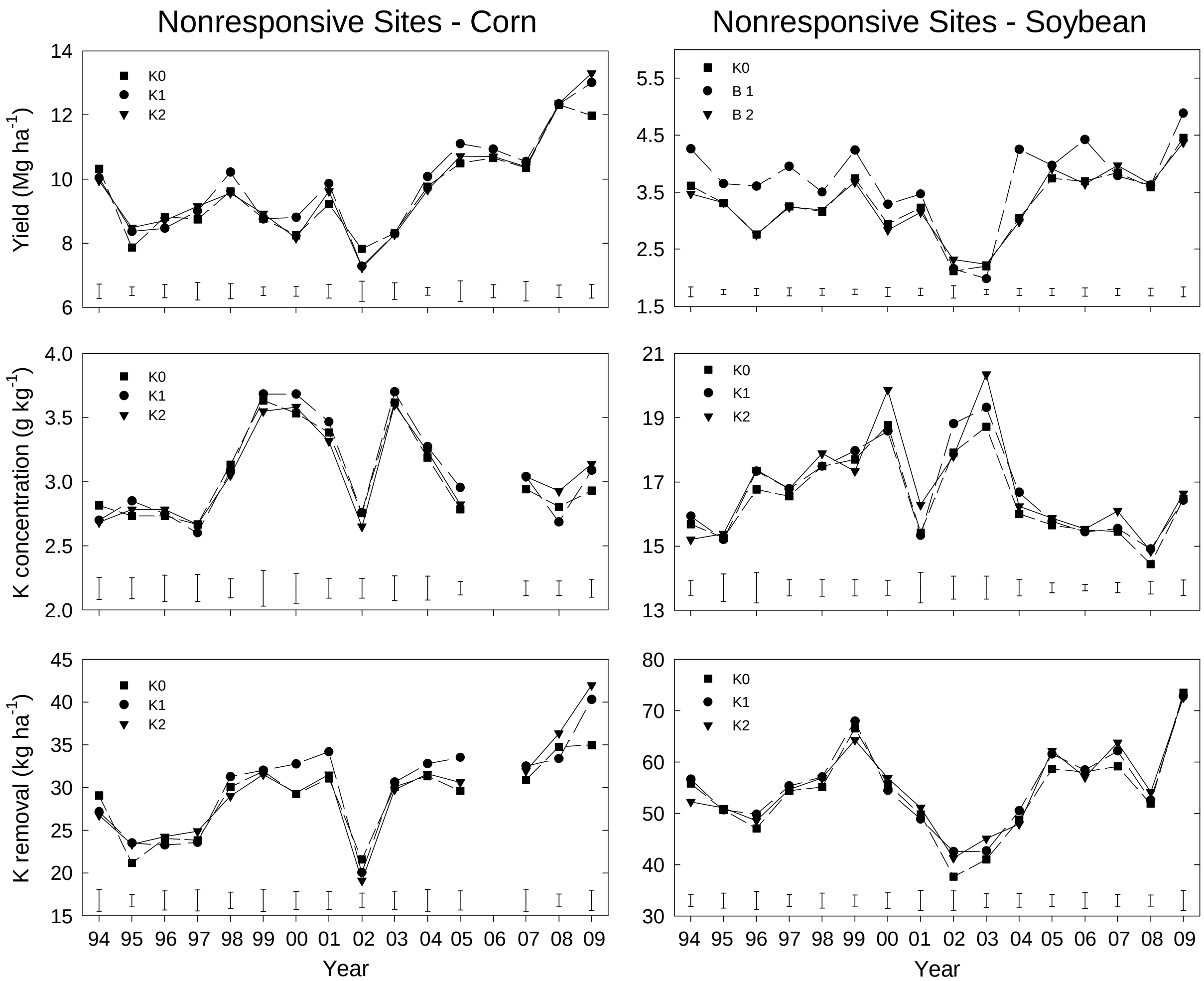

Figure 2. Mean trends over time for yield, grain K concentration, and K removal across the two yield responsive sites (NWRF AND SWRF). K0 refers to the control (0 kg K ha^{-1}) treatment and K1 and K2 refers to 33 and 66 kg K ha^{-1} respectively. Corn grain samples were lost in 2006, so no data was included for any treatment. Vertical lines at the bottom of each graph indicate standard errors of a treatment mean for each year.

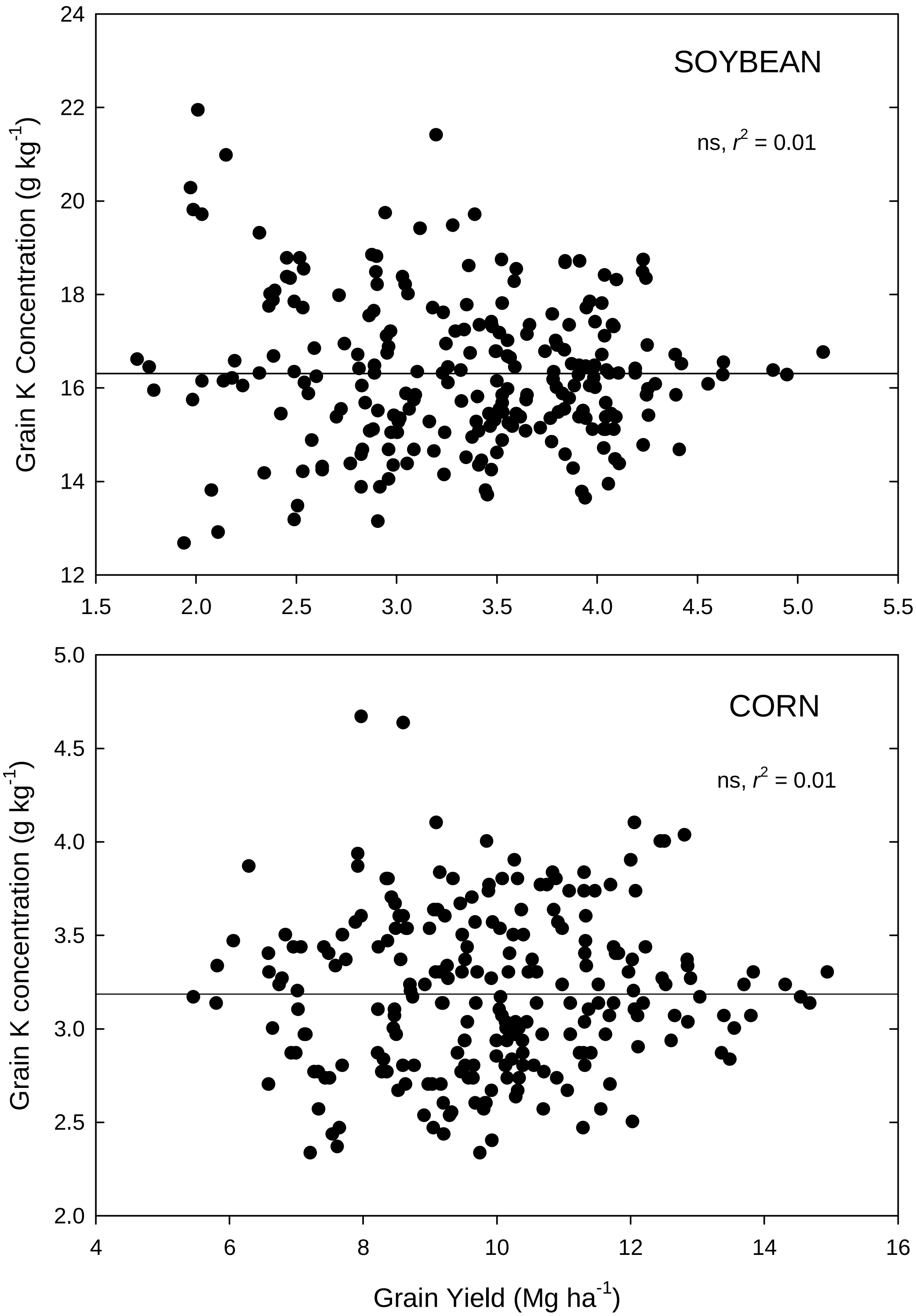

Figure 3. Relationship between grain yield and grain K concentration across all sites, years, and treatments.

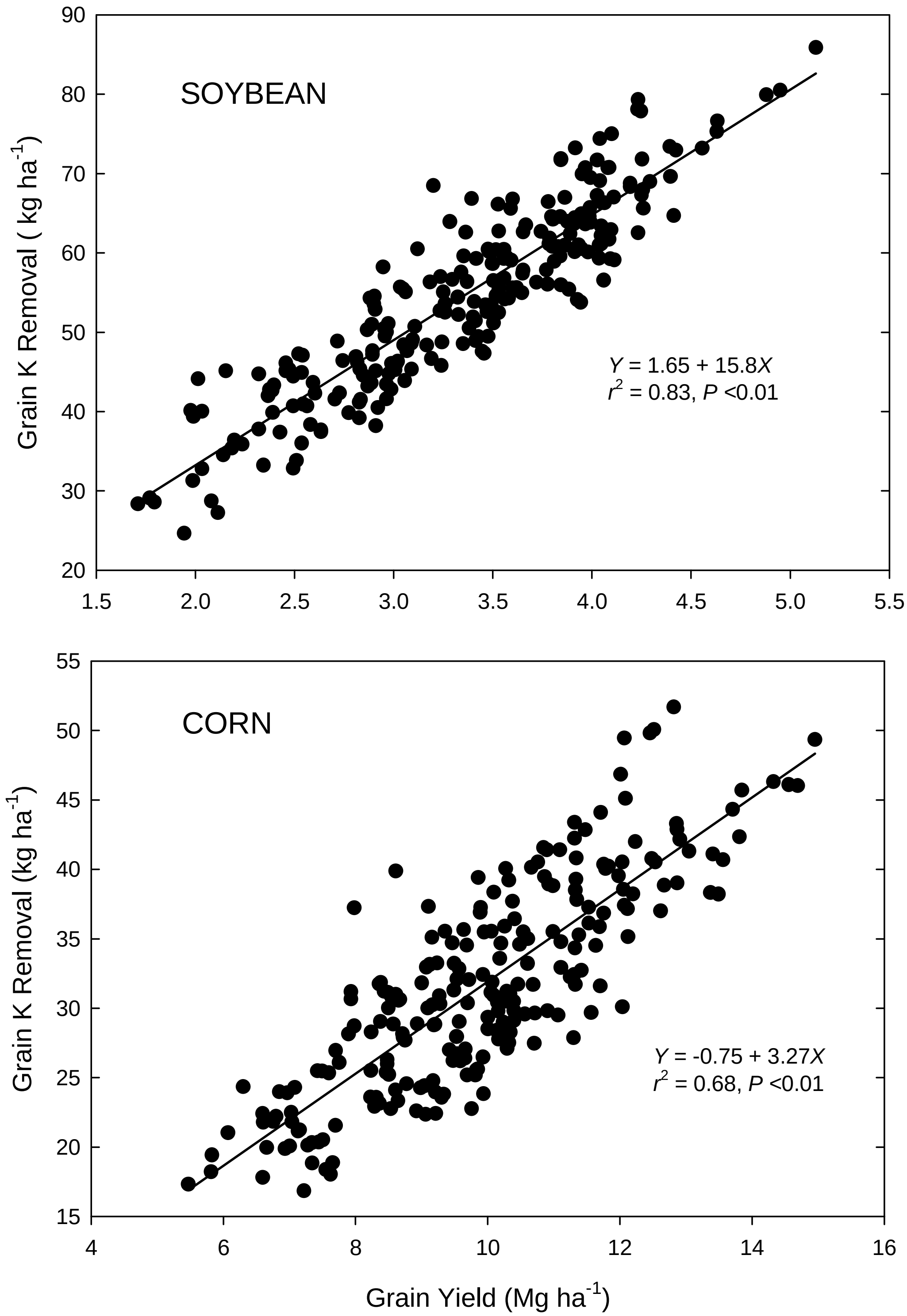

Figure 4. Relationship between grain yield and K removal with grain harvest across all sites, years, and treatments.

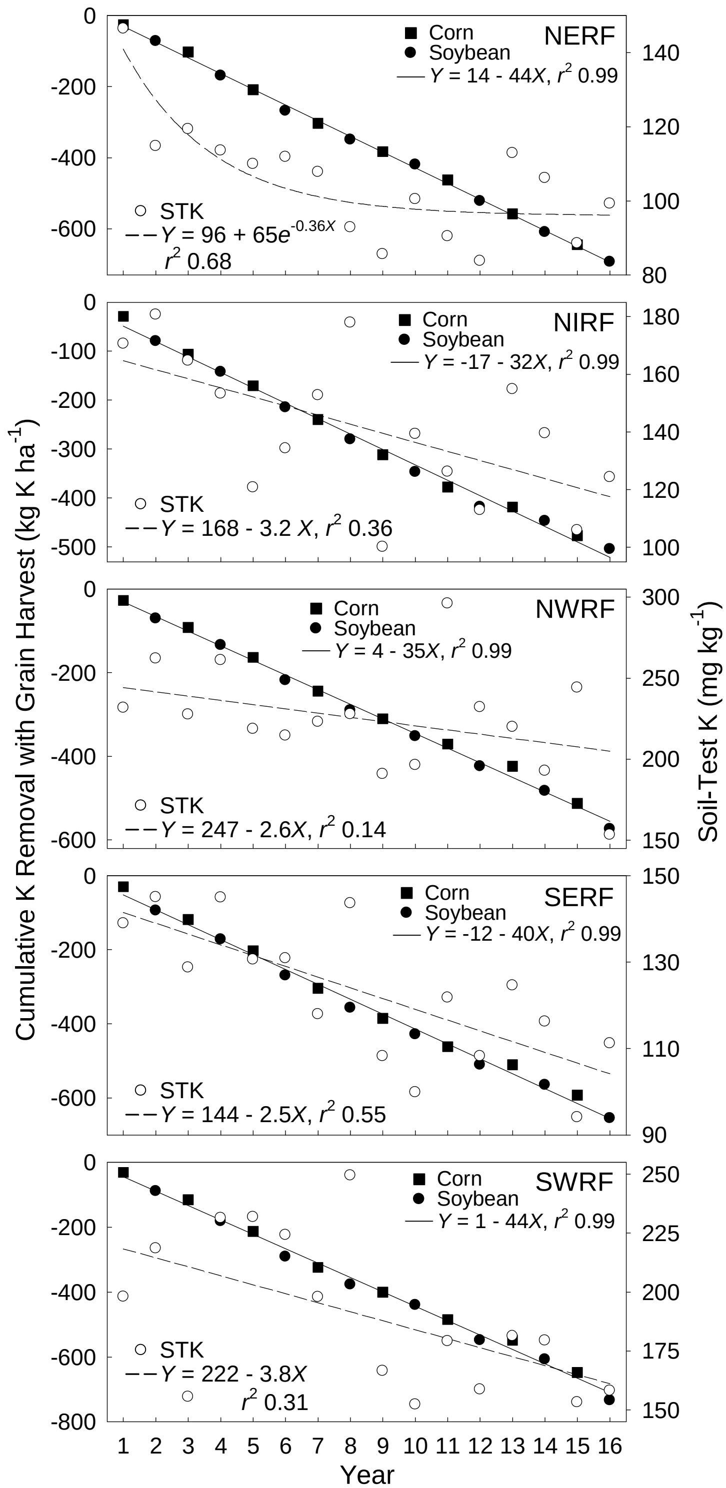

Figure 5. Trends over time for cumulative K removal with grain harvest and soil-test K for samples collected each year from the non-fertilized plots.

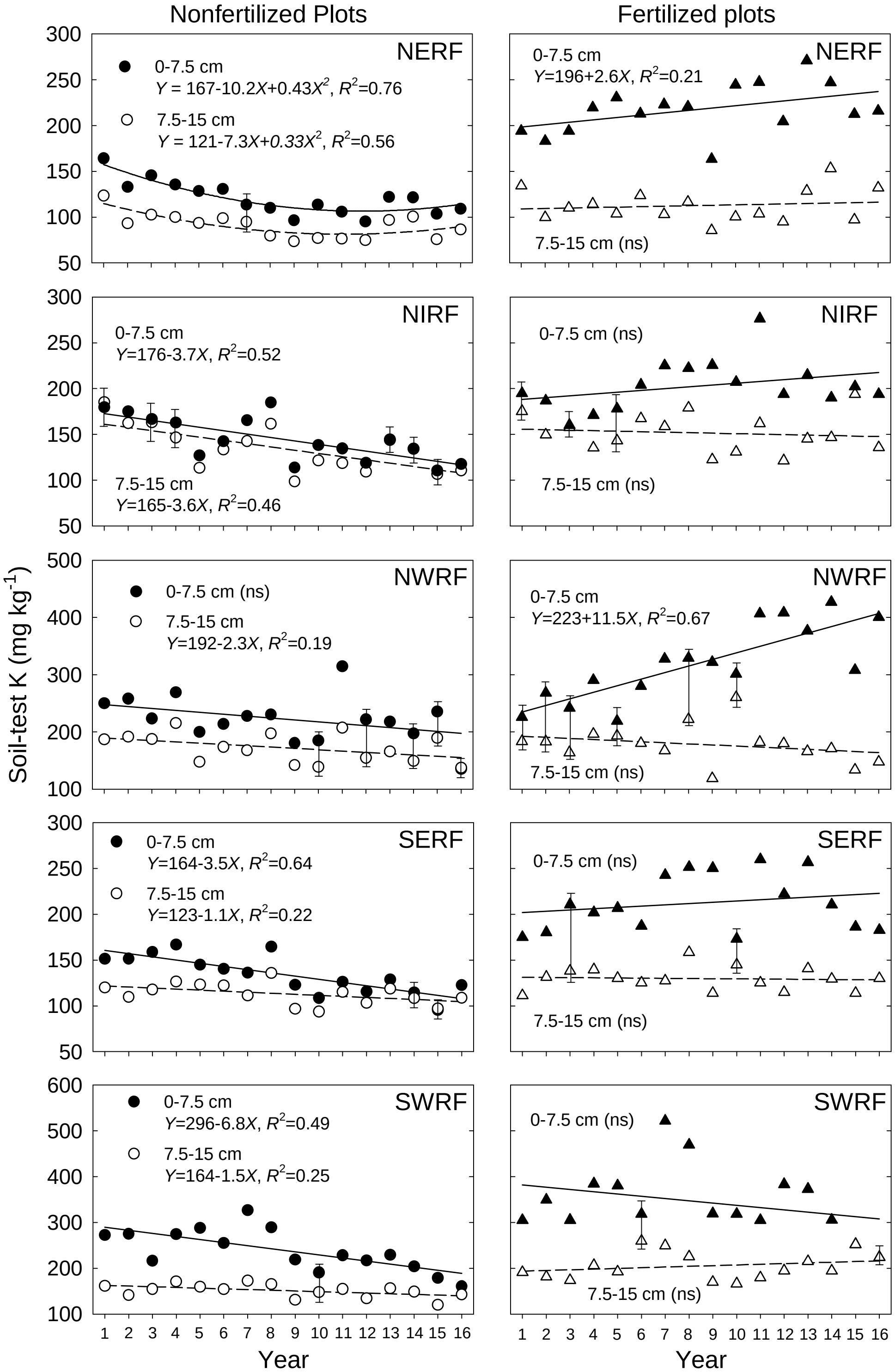

Figure 6. Soil-test K trends over time for two depths and for fertilized and non-fertilized plots. The fertilized plots sampled until 1999 received 66 kg K ha^{-1} yr^{-1} and plots sampled since 2000 received 132 kg K ha^{-1} yr^{-1} only in even years. Vertical lines encompassing two depths indicate no depth difference ($P < 0.10$).

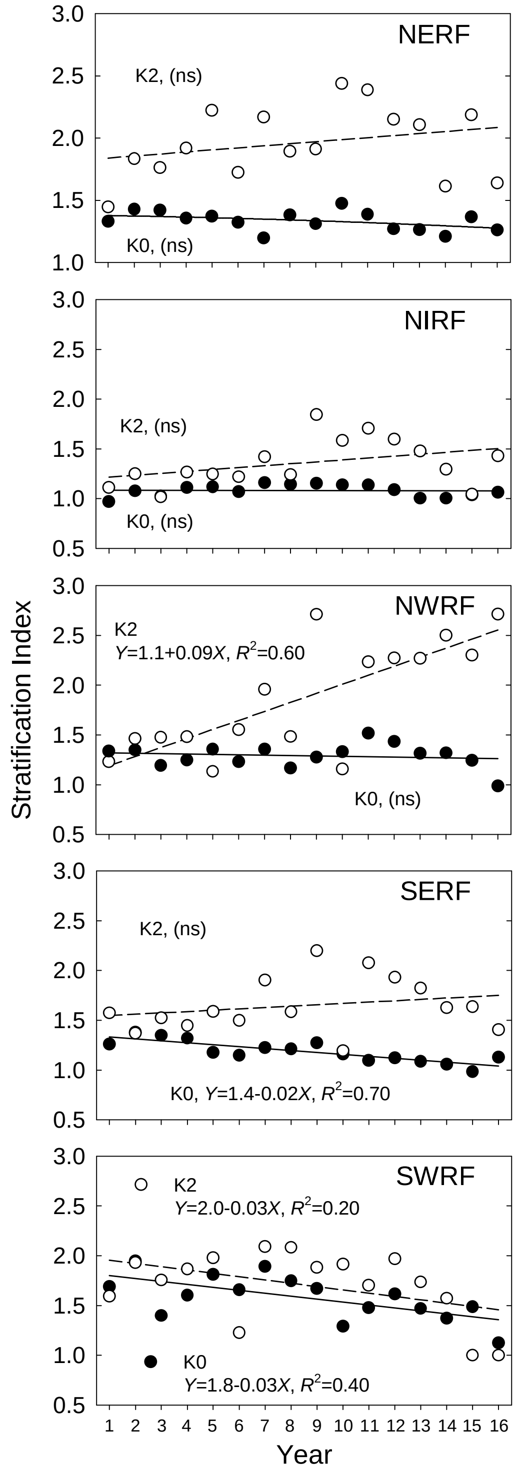

Figure 7. Trends for a soil-test K stratification index for fertilized (K2/3) and non-fertilized (K0) plots. The index was calculated as STK in the top 7.5-cm depth divided by STK in the 7.5-15 cm depth. The fertilized plots sampled until 1999 received 66 kg K ha^{-1} yr^{-1} and plots sampled since 2000 received 132 kg K ha^{-1} yr^{-1} only in even years.

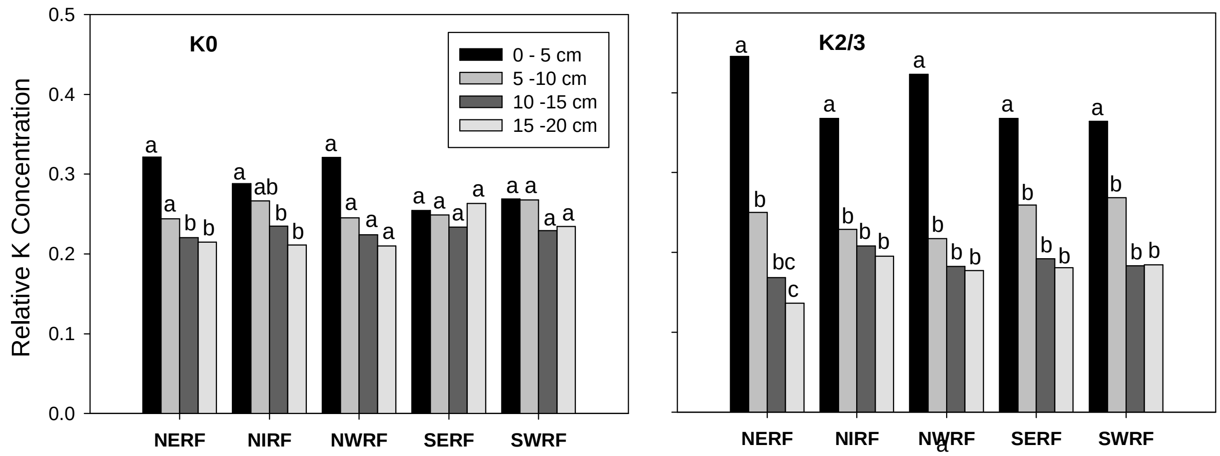

Figure 8. Relative soil-test K distribution in the top 20 cm of the soil profile for samples collected after the last soybean harvest in fall 2009 from fertilized plots (K2, 66 kg K ha^{-1} yr^{-1}) and non-fertilized plots (K0). Relative values indicate for each site and K rate the proportion of soil-test K in each layer (from a total of one).

CHAPTER 3. GENERAL CONCLUSIONS

Results from this 16-year study conducted at five Iowa locations confirmed the importance of long-term evaluations of soil-test K (STK), K removal with grain harvest, and crop yield as affected by the potassium (K) fertilization rate to better understand processes underlining K relationships and improve fertilization programs.

An important conclusion of the study was that there was significant stratification of STK in the top 20-cm of soil at all sites, which tended to be proportionally larger for the fertilized plots. However, there was no clear or consistent change over time in stratification across sites for non-fertilized or fertilized plots. This result was explained by fertilization rates that in general did not increase STK significantly over time. The only clear stratification increase over the 16 years of the study was observed for the one site where K fertilization significantly increased STK of the shallowest sampling depth over time.

Another important conclusion was that crop yield response to K fertilizer application for sites where initial STK was in the Low soil-test interpretation class, and also in two sites with initially Optimum STK that decreased to a Low level over time. The frequency and magnitude of the responses tended to increase over time, which is expected as STK of non-fertilized plots declines. No frequent or large yield responses were observed when STK was in the High or Very High interpretation classes. Potassium fertilization had less frequent and smaller effects on grain K concentration (GKC) of both crops compared with effects on yield. The observed average GKC in this study were lower than the average values suggested in Iowa fertilization guidelines. The currently suggested averages for both crops were in the upper range of observed values. Potassium removal with grain harvest tended to follow trends for yield levels and for yield responses, because differences were proportionally much higher than differences in GKC. Therefore, these results suggest that good yield estimates are more important than GKC estimates to estimate grain K removal over time.

Another significant conclusion of the study was that K removal decreased linearly over time at all sites and that STK also decreased usually linearly, although at one location STK reached a plateau at a very low level. There was a very high temporal variability of STK as identified by post-harvest soil sampling every year. This variability was not well correlated with K removal in the short term, but relationships between the two measurements were better over several years. The relationship between the two rates of decline varied across sites, however, and could not be fully explained on the basis of K removal and measured soil properties such as texture, extractable cations, or cation exchange capacity. These differences might be explained by other soil properties, such as mineralogy, and environmental factors influencing K recycling with crop residue and the estimate of crop-available soil K by soil testing.

Overall, the results of this study made significant contributions to knowledge of K relationships in soils under a no-till management system, and also provided useful information to improve K management guidelines for production agriculture.

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